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The DURIP funds generously provided by the AFOSR were used to set up a state-of-the-art facility for fabricating in-fiber photrefractive and planar waveguide surface etched Bragg gratings. These gratings are being investigated for such defense-relevant projects as high temperature sensors, distributed and multiplexed strain and temperature sensors, bio-agent sensors and wavelength division multiplexed telecommunication systems. In this report, we briefly describe (1) the fundamentals of Bragg gratings in fibers and in planar waveguides (2) the grating fabrication facility made possible by DURIP funding and (3) our progress on the grating fabrication process in the following sections.

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Dear Dr. Jones:

Attached please find the final technical report for the subject grant.

Should you have any questions or require additional information regarding this grant please feel free to contact me at (301)405-6273.

Sincerely,

Evan Crierie

Evan Crierie
Contract Administrator

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Enclosures

cc: C. Witherspoon, Mech. Eng.

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Bragg Grating Fabrication and Characterization

A Final Technical Report

Submitted to the Airforce Office of Scientific Research

by

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Summary

The DURIP funds generously provided by the AFOSR were used to set up a state-of-the-art facility for fabricating in-fiber photorefractive and planar waveguide surface etched Bragg gratings. These gratings are being investigated for such defense-relevant projects as high temperature sensors, distributed and multiplexed strain and temperature sensors, bio-agent sensors and wavelength division multiplexed telecommunication systems. In this report, we briefly describe (1) the fundamentals of Bragg gratings in fibers and in planar waveguides (2) the grating fabrication facility made possible by DURIP funding and (3) our progress on the grating fabrication process in the following sections. Table 1 provides a list of equipment items we purchased using DURIP funds, the vendors, vendor's phone numbers and the approximate costs.

Instrumentation	Manufacturer	Phone	Cost
FReD Laser and Accessories	Coherent Laser Group, CA	1-800-527-3786	$80,000
Optical Spectrum Analyzer	Hewlet Packard	301-258-5997	$51,865
Optical Isolation Table	Melles Griot	1-800-835-2626	$10,275
3 Custom Phase Masks	Lasiris Inc. Canada	1-800-814-9552	$,4,800
UV Optics and Mounting Accessories	Melles Griot Newport Corp. Optics For Research	1-800-835-2626 1-800-222-6440 201-228-4480	$,4,349
Pressure Vessel and Temp.Controller	Parr-Instrument Company, IL	1-800-872-7720	$3,800
UV Power Meter	Gentec, Canada	415-321-4258	$1,625
Motorized Stages and Softwares	Dina Optics Motion, CA	714-770-2492	$12,000
Clean Room	Liberty, CT	1-800-828-5656	$6,087
Total			**$174,801**

Table 1. Equipments acquired for Bragg grating manufacturing

1.0 Introduction to Bragg Gratings

The research involving Bragg gratings can be divided into two major areas, one that utilizes In-Fiber Bragg Gratings (IFBG) and the other that utilizes surface type or Planar Waveguide Bragg Gratings. Though the theory behind these gratings are governed by the same coupled mode theory, their step by step fabrication process, measurements and hence the characterization methods are not similar. We therefore try to describe these two categories separately in this report.

1.1 In-Fiber Bragg Gratings

An in-fiber Bragg Grating is a periodic perturbation of refractive index in the fiber core along the fiber length. These physically invisible gratings are a consequence of UV photosensitivity of the core material. The period of the grating can vary from a tenth of a micron to a couple of microns. If white light is injected into the fiber containing an in-fiber Bragg grating as illustrated in Figure 1, a specific wavelength that satisfies the Bragg phase or momentum condition will then be reflected. This narrow band filtering property is being used for several applications in fiber optic communication and sensors. Figure 1 shows a schematic set up for investigating reflected Bragg spectrum and a typical such spectrum captured by a HP 70951B optical spectrum analyzer purchased using DURIP funds.

1.2 Planar Waveguide Bragg Gratings

Unlike the index modulation grating in optical fibers, the planar waveguide gratings are relief type gratings [1] chemically etched into the surface of a thin layer of Ge-doped silica substrates. Etched planar waveguide gratings couple light the same way in-fiber gratings do. These planar waveguide grating structures are commonly used for components in integrated optics. We have selected the planar waveguide structure for investigation because integrated optics have a number of advantages when compared to conventional optical signal processing systems. Planar waveguide structures are small size and weight, as well as have low power consumption and improved reliability. Planar waveguide relief grating microfabrication processes include optical and electron-beam lithography.

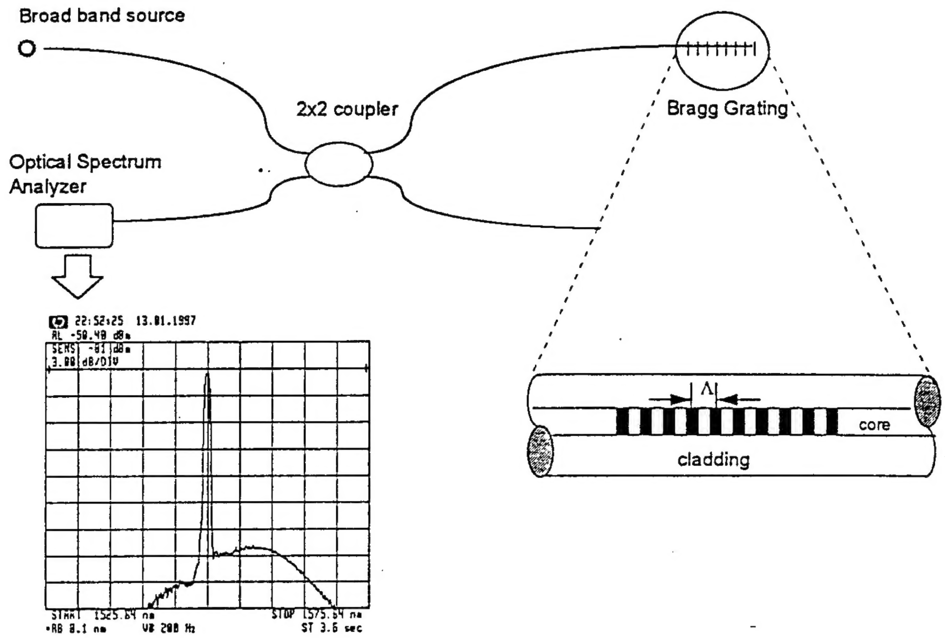


Figure 1. Typical arrangement to investigate IFBGs

2.0 Grating Fabrication Facility

Bragg grating fabrication is carried out by exposing the fiber or planar waveguide to coherent optical interference patterns that form a periodic intensity variation. It is essential to have a vibration free and dust free environment in order to maintain the stability of this interference pattern during the fabrication. DURIP funds enabled us to build a class 1000 clean room facility for this purpose. Figure 2 shows a photograph of the clean room facility. The clean room itself consists of a 21 ft x 6 ft working space enclosed by clear plastic walls. The ceiling of the clean room contains lighting, HEPA filters and power conduits. The centerpiece of the fabrication facility housed in the clean room is a frequency doubled Argon-Ion (FReD) laser. This laser emits light at different wavelengths with the strongest at 488 nm. After frequency doubling, this line gives highly coherent light of wavelength 244 nm. This clean room facility also includes a computer controlled motorized rotational and translational stages for accurate, easy and smooth adjustments of the optics and a HP 70951B model Optical Spectrum Analyzer for monitoring the grating growth. The optical system used to manufacture gratings resides on a Melles Griot 4 ft x 12 ft x 1" isolation table. Each of the major items purchased using DURIP funds is labeled in the photograph shown in Figure 2.

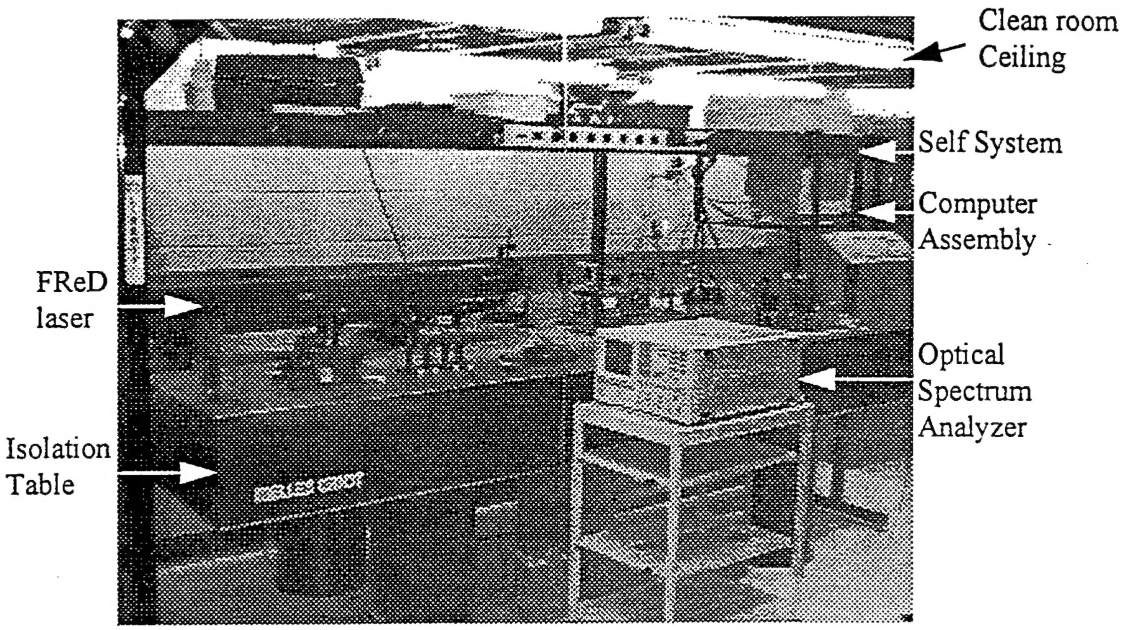


Figure 2. The class 1000 clean room and the grating fabrication facilities

3.0 Past Work and Results

3.1 In-Fiber Bragg Gratings

In order to enhance the photosensitivity of gemanosilicate fibers we use a high pressure hydrogen loading method [2]. The process is carried out by exposing the single mode Ge-doped fiber to pure hydrogen to a combined temperature and pressure of 50^0C and 1500 psi for more than 100 hours. The pressure vessel used to perform this process and the heater system are shown in Figure 3. This 450 ml volume pressure vessel consists of a general purpose cylinder bomb which is made of special type of Stainless Steel and has a safety rupture disk made of Inconnel. The temperature in the pressure vessel is controlled using an industrial PID controller.

We have used two methods of fabricating fiber gratings, namely, holographic interference method and phase mask contact imprinting method [3,4]. Each method has advantages and disadvantages. The phase mask method is easier to set up, to control, more accurate and more stable while the holographic set up is more sensitive to vibrations and requires very careful adjustments. On the other hand, the advantage of holographic method is the flexibility of writing any preferred Bragg wavelength, which is not possible with the phase mask method. We have completed both arrangements and started writing Bragg gratings using the phase mask optical arrangement shown schematically and photographically in figure 4.

Gratings are written in hydrogen loaded single mode fiber using the 244 nm UV light using optical powers ranging from 20 mW to 30 mW at the phase mask. The writing power of the laser light is measured by a UV power meter purchased from Gentec Company using DURIP funds. So far we have been able to write gratings at different wavelengths centered at 1550 nm, 1535 nm and 1300 nm with peak reflectivities as high as 99%. The bandwidth of these gratings, which is a function of grating length, peak index modulation and the period of the phase mask grating [5] varied from 0.2 nm to 0.5 nm.

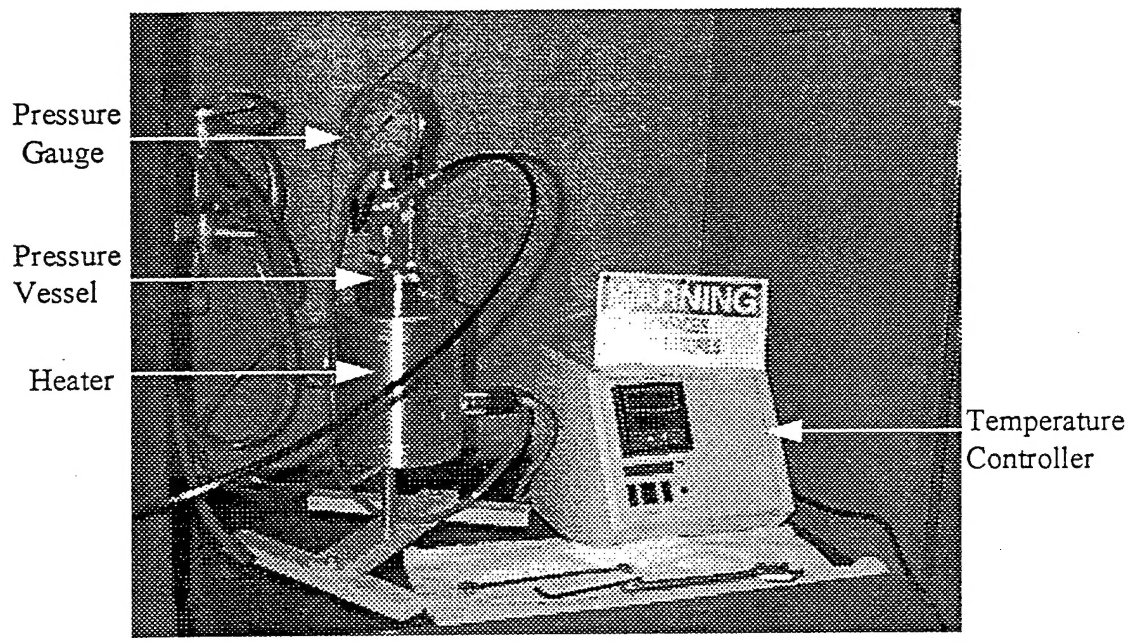


Figure 3. Hydrogen loading temperature controlled pressure vessel

We investigated the use of different fibers including Corning SMF 28, Corning SMF28/DS, Spectran SMB-E1310B and Spectran SMT-A1310B and found that the Corning SMF28/DS fiber has the fastest response to UV irradiation, giving rise to the shortest writing time. Figure 5 below shows the transmission spectra of gratings in different fibers. All these fibers were loaded with hydrogen under the same conditions mentioned above for about 5 days. In Figure 5(a) the spectrum shows a saturated behavior which leads to wide band width and high apodizing effect. The exposure time for this fiber was about 10 minutes. Figure 5(b) and 5(c) show different reflectivities of the respective fibers for same the exposure time (~ 6 min). The Spectran SMB-E1310B fiber has faster response than SMF 28 fiber but the bandwidth appears to be larger than the other fiber types. This could be a consequence of birefringent nature of the Spectran fiber. All these gratings have been tested for drift in wavelength and reflectivity.

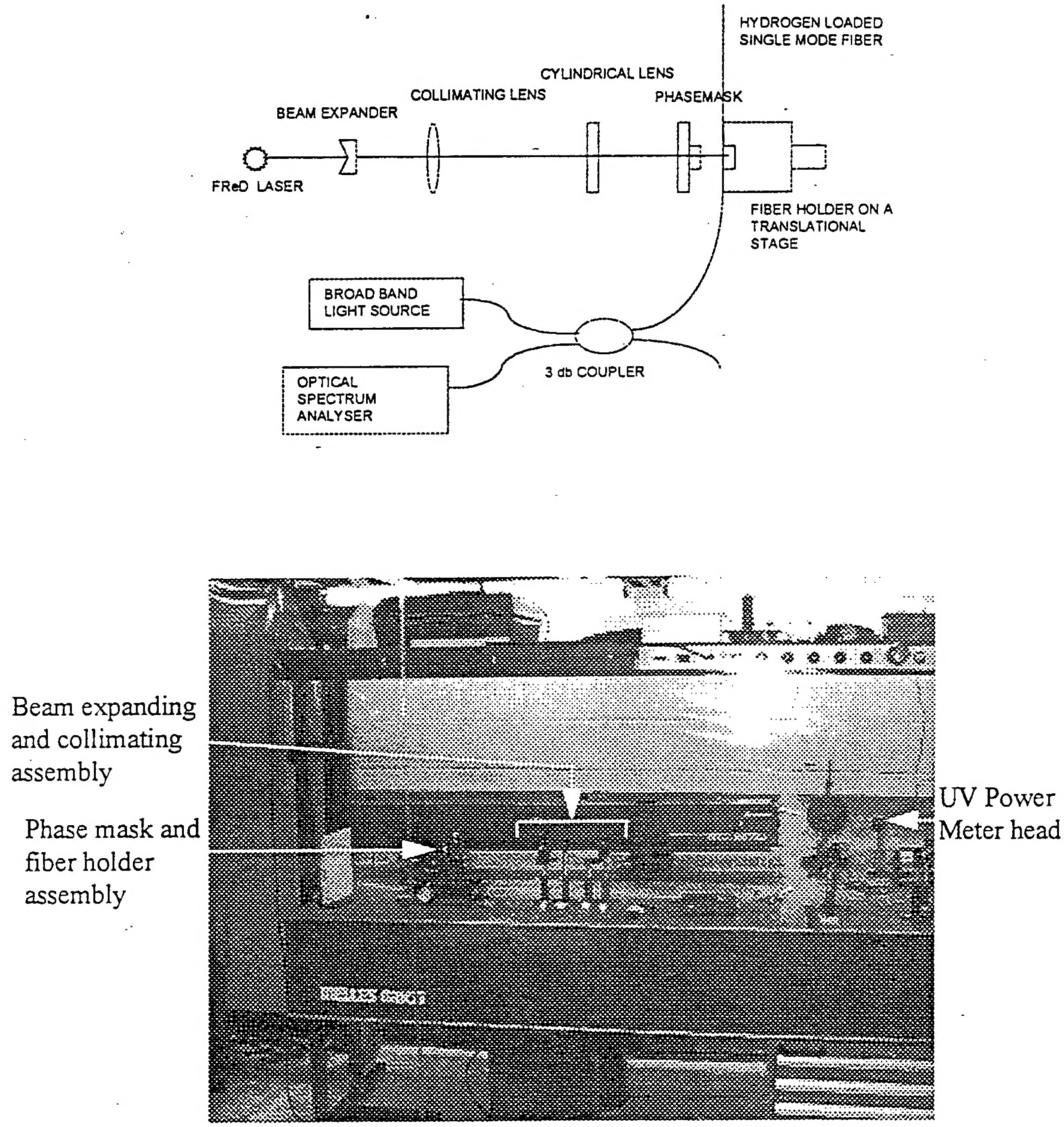
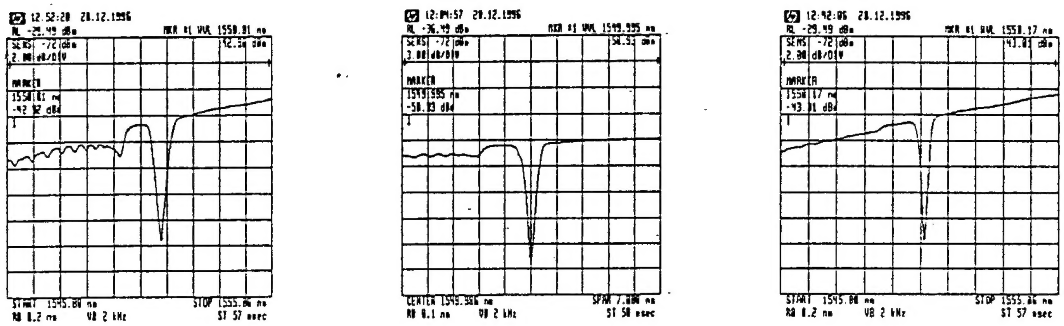


Figure 4. The phase mask set up for in- fiber Bragg grating imprinting



(a) (b) (c)

Figure 5. Transmitted Bragg spectrum in a) Spectran SMB-A1301B b) Corning SMF 28/DS and c) Corning SMF 28 fibers.

3.2 Planar waveguide Gratings

The approximate solution to the rectangular channel waveguide problem as derived by Marcatili [6] was applied to design the structure of Ge-doped silica-based single mode waveguide. The Ge-doped Silica core waveguide (refractive index~1.4509) with an 8 micron cross-section was designed. The index difference between the core film and the buffer layer was 0.28 percent. These waveguides were fabricated for us by Photonic Integration Research, Inc.(PIRI) using flame hydrolysis deposition (FHD) and reactive ion etching (RIE) techniques. The overcladding layer that covers the core waveguide was carefully polished until the core layer is exposed to the air. Figure 6 shows a photograph of the cross-section of one of the polished channel waveguides we are using.

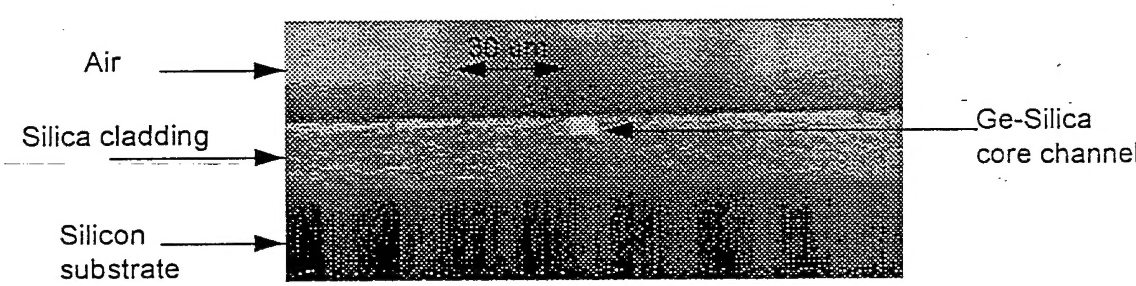


Figure 6. The photograph of the cross-section of a channel waveguide

The gratings are etched into Ge-doped silica core of channel waveguide such as the one shown in Figure 6. This is done by first spin-coating with Shipley S1400-17 photoresist that is thinned to give a thickness of less than 200 nm, and then baked for 30 min at 90° C. Holographic gratings are fabricated by interfering two beams using the setup shown in Figure 4. In this setup, instead of beam splitter we used a phase mask to produce two high quality optically uniform beams with equal intensity. An exposure time of 8 sec, when laser power is about 2 mW, is typical. After developing the substrates, they are baked for 30 min at 120° C. To transfer the grating into the silica substrates, the gratings are chemically etched to a depth of 80 nm using a buffered HF solution. The photoresist is then stripped to investigate the reflectivity of the gratings using both atomic force microscope (AFM) and Environment Scanning Electron Microscope (ESEM). The pitch of the gratings fabricated in this way are approximately 530 nm. Figure 7 shows a photograph of a waveguide grating. This image was generated by an atomic force microscope.

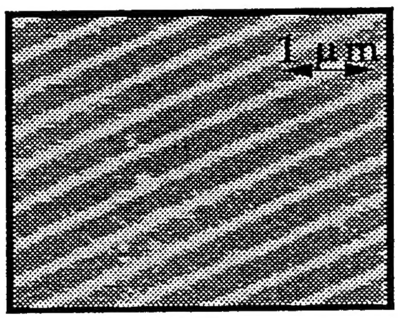


Figure 7. The photograph of the etched gratings.

4.0 Current work

4.1 In-Fiber Bragg Gratings

One of the main advantages of holographic fabrication method is that the flexibility in writing many gratings with different Bragg wavelengths using the same setup. Figure 8 shows a schematic of the optical arrangement we are developing for the holographic processing technique. The UV light passes through a set of lens that expand and isolate the central lobe of the laser emission. The second set of lens is where the holographic process takes place. First, the beam is passed through a collimating lens in order to focus it onto the fiber. The beam then passes through a beam splitter which breaks the light into two equal beams traveling at 90 degrees relative to each other. Each of these beams is then reflected by a mirror towards the target fiber. It is at this location where the 2 beams create the interference pattern that causes the desired modulation of the refractive index in the fiber.

The Bragg wavelength of the manufactured grating is determined by the half-angle θ between the two interfering beams. In order to vary this angle θ, we have placed the fiber holding assembly on a linear motorized computer controlled stage, and the two mirrors on rotational motorized computer controlled stages. This will allow us to easily and accurately position these optical components to manufacture Bragg gratings at any wavelength between 800 nm and 1600 nm. The cylindrical lens is also placed on a linear motorized computer controlled stage in order to keep the distance from the cylindrical lens and fiber holder constant (i.e. the focal length of the lens). Due to limitations on the linear motorized stages, only 15 cm of linear motion, care must be taken when setting up the system to ensure that the desired wavelength range will be able to be manufactured. Bragg gratings outside of the above stated range can also be made; however, in order to perform such a task the linear motorized stages will have to be moved in order to provide the proper physical dimensions to the system. In other words, to allow the angle θ to vary over a different range. Work is currently being done to setup the translational and rotational stages with the optical components, and writing computer programs to move the stages to the proper locations for manufacturing of gratings. Design considerations such as physical limitations of the stages, accuracy of the stages, properties of the optical components, and desired Bragg grating wavelengths are being considered in each step of this process. Figure 9 shows a photograph of our preliminary holographic setup. In this setup the cylindrical lens and the fiber holder assembly are mounted on linear translational stages while the highly reflective mirrors are mounted on the rotational stages as depicted in the schematic diagram. The beam flipper unit enables us to switch the beam to either side so that the phase mask and holographic arrangements can be used whenever required without rearranging anything but the beam flipper.

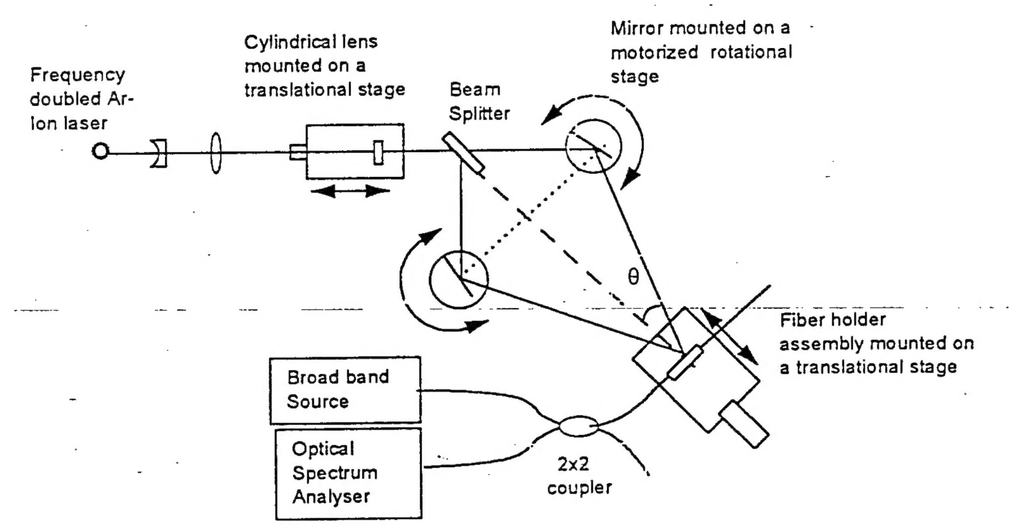


Figure 8. Schematic holographic set up

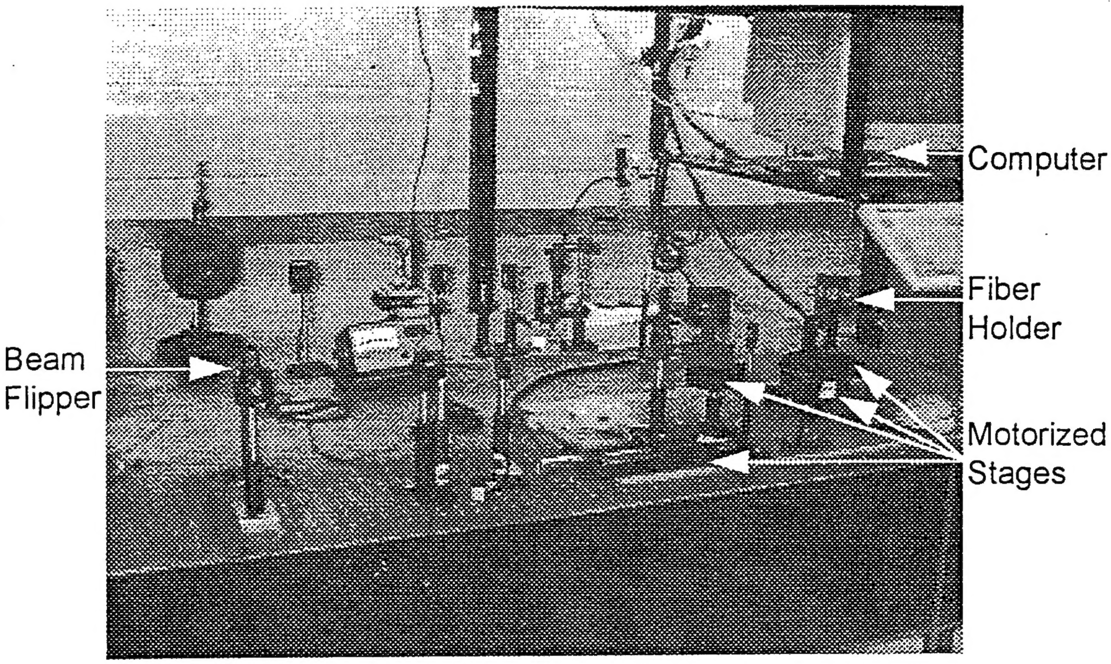


Figure 9. The holographic set up for in-fiber Bragg grating fabrication

4.2 Planar waveguide Gratings

We are currently optimizing grating properties using design codes we developed. These design codes are based on a set of coupled-mode equations [7]. These codes allow us to determine the etching parameters required to enhance reflectivity. We are also working on lower insertion loss methods to couple single mode fiber to the planar waveguide gratings. The insertion loss in waveguide includes coupling loss and propagation loss (both scattering and absorption). Assuming perfect alignment between the fiber to silica waveguide, the two dominating contributions to fiber-waveguide coupling loss are Fresnel loss (reflection) and the loss caused by mismatch between the fiber and waveguide modes. In our present approach the end faces of the waveguide were diced and carefully polished. The Fresnel loss is greatly reduced by using index-matching fluid on the silica substrate end faces. We are trying to achieve the single-mode fiber alignment more accurately with micromanipulators on the optical microscope.

5.0 Near future plans

5.1 In-Fiber Bragg Gratings

Our near future work will be focused on the grating quality and reliability studies especially the parameters that changes the band width of the gratings. We also will look into the possibility of high temperature annealing process for long term grating stability. Successful process of high temperature annealing will allow us to develop strain and temperature sensors for temperatures reaching up to ~700 ^{0}C.

5.2 Planar Waveguide Gratings

To achieve the efficient fiber-waveguide coupling, we will continue to develop the butt coupling techniques with the etched waveguide. We will continue to examine the spectral characteristics of the reflected and transmitted light to investigate the grating parameters. Once reliable coupling techniques are developed, we will be in a position to begin developing strain and temperature sensors for temperatures exceeding 1000 ^{0}C.

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